STUDIES ON MAJOR ELEMENTS OF AN ELEVATED METRO BRIDGE

KUPPUMANIKANDAN A

ROLL NUMBER: 211CE2019

Department of Civil Engineering
National Institute of Technology Rourkela
Odisha – 769008

STUDIES ON MAJOR ELEMENTS OF AN ELEVATED METRO BRIDGE

A thesis

Submitted by

KUPPUMANIKANDAN A

Roll Number: 211CE2019

in partial fulfilment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

STRUCTURAL ENGINEERING

Department of Civil Engineering

National Institute of Technology Rourkela

Odisha – 769008

MAY 2013

STUDIES ON MAJOR ELEMENTS OF AN ELEVATED METRO BRIDGE

A thesis

Submitted by

KUPPUMANIKANDAN A

Roll Number: 211CE2019

in partial fulfilment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

STRUCTURAL ENGINEERING

Under the Guidance of

Prof. Robin Davis P, NIT Rourkela

Shri N.P. Sharma, BMRC Limited, Bangalore

Department of Civil Engineering
National Institute of Technology Rourkela
Odisha – 769008

MAY 2013

Department of Civil Engineering
National Institute of Technology Rourkela
Rourkela, Odisha – 769008

THESIS CERTIFICATE

This is to certify that the thesis entitled **"STUDIES ON MAJOR ELEMENTS OF AN ELEVATED METRO BRIDGE"** submitted by **KUPPUMANIKANDAN A** bearing Roll Number: **211CE2019,** in partial fulfilment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in "Structural Engineering" at National Institute of Technology Rourkela, is a bonafide record of project work carried out by him under our supervision. To the best of our knowledge, the contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Project Guides

Prof. Robin Davis P
Department of Civil Engineering,
NIT Rourkela,
Rourkela.

Shri N. P. Sharma
Chief Engineer,
BMRC Limited,
Bangalore.

ACKNOWLEDGEMENTS

Knowledge in itself is a continuous process. I would have never succeeded in completing the task without the cooperation, encouragement and help provided by various personalities.

At this point, I like to express my sincere heartfelt thanks and appreciation to my guides **Prof. Robin Davis P,** Assistant Professor, Department of Civil Engineering, NIT Rourkela and **Shri N. P. Sharma,** Chief Engineer, Bangalore Metro Rail Corporation Limited, Bangalore. I am greatly indebted to them for their unwavering commitment, thought provoking and constructive comments to improvise the quality of my work. They have always been a source of inspiration and encouragement and have helped me tide over many a rough patch in my project. It gives me immense pleasure to thank them for sparing their precious time with me in all my tough times.

My special thanks to **Prof. S. K. Sahu and other faculty members** of Department of Civil Engineering, NIT Rourkela for conducting the project reviews at regular intervals, which enables me to be in constant touch with my project and for giving me valuable suggestions at various stages of the project reviews to extract quality and professionalised work from me. Also, I would like to thank our beloved Head of the Department, **Prof. N. Roy** for his support and encouragement throughout the project.

I am grateful to our beloved Director, **Prof. S. K. Sarangi**, and **Shri. B. S. Sudhir Chandra**, Chairman, Board of Governors, NIT Rourkela and Director (Project and Planning), Bangalore Metro Rail Corporation Limited, Bangalore for giving me an opportunity to do this intriguing project.

Last but not the least I thank all my family members and close friends for their constant motivation and support without which this work would not have been possible.

KUPPUMANIKANDAN A

ABSTRACT

Keywords: *Elevated Metro Structure, Bridge Pier, Box Girder Bridge, Direct Displacement Based Seismic Design, Performance Based Design, Force Based Design*

A metro system is a railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. Metro System is used in cities, agglomerations, and metropolitan areas to transport large numbers of people. An elevated metro system is more preferred type of metro system due to ease of construction and also it makes urban areas more accessible without any construction difficulty. An elevated metro system has two major elements pier and box girder. The present study focuses on two major elements, pier and box girder, of an elevated metro structural system.

Conventionally the pier of a metro bridge is designed using a force based approach. During a seismic loading, the behaviour of a single pier elevated bridge relies mostly on the ductility and the displacement capacity. It is important to check the ductility of such single piers. Force based methods do not explicitly check the displacement capacity during the design. The codes are now moving towards a performance-based (displacement-based) design approach, which consider the design as per the target performances at the design stage. Performance of a pier designed by a Direct Displacement Based Design is compared with that of a force-based designed one. The design of the pier is done by both force based seismic design method and direct displacement based seismic design method in the first part of the study.

In the second part, a parametric study on behaviour of box girder bridges is carried out by using finite element method. The finite element model is validated with model of Gupta et al. (2010). The parameters considered to present the behaviour of Single Cell Box Girder, Double Cell Box Girder and Triple Cell Box Girder bridges are radius of curvature, span

length and span length to the radius of curvature ratio. These parameters are used to evaluate the responses of box girder bridges namely, longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency of three types of box girder bridges.

The performance assessment of selected designed pier showed that, the Force Based Design Method may not always guarantee the performance parameter required and in the present case the pier achieved the target requirement. In case of Direct Displacement Based Design Method, selected pier achieved the behaviour factors more than targeted Values. These conclusions can be considered only for the selected pier.

The parametric study on behaviour of box girder bridges showed that, as curvature decreases, responses such as longitudinal stresses at the top and bottom, shear, torsion, moment and deflection decreases for three types of box girder bridges and it shows not much variation for fundamental frequency of three types of box girder bridges due to the constant span length. It is observed that as the span length increases, longitudinal stresses at the top and bottom, shear, torsion, moment and deflection increases for three types of box girder bridges. As the span length increases, fundamental frequency decreases for three types of box girder bridges. Also, it is noted that as the span length to the radius of curvature ratio increases responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges. As the span length to the radius of curvature ratio increases fundamental frequency decreases for three types of box girder bridges.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

English Symbols

A	Coefficient of Thermal Expansion
A_h	Design Horizontal Seismic Coefficient
E	Modulus of Elasticity
f_c'	Specific Concrete Compressive Strength
G	Modulus of Rigidity or Shear Modulus
h	Height of the building
H	Column Height
h_c	Section Depth of Rectangular Column
I	Importance factor
K_e	Effective Stiffness at peak response
L_{sp}	Effective additional height representing strain penetration effects
R	Force Reduction Factor
R'	Behaviour factor
R_μ	Ductility Reduction factor
R_s	Over Strength Factor
Sa/g	Average response acceleration coefficient
T	Fundamental Time Period
T_e	Effective response period of pier
V_B	Design Seismic Base Shear
V_e	Elastic response strength
V_s	First significant yield strength

V_w	Allowable stress design strength
V_y	Idealised yield strength
W	Seismic weight of the building
Y	Allowable stress factor
Z	Zone factor

Greek Symbols

ξ	Damping
$\Delta_{c,n}$	Displacement at the corner period for n % damping
μ	Displacement Ductility
α	Non Dimensional Ratio Curved to Straight Girder
Δ'_{max}	Maximum Structural Drift
Δ_d	Design Displacement
Δ_y	Yield Displacement
ε_y	Yield Strain of pier
θ_d	Drift Limit
μ'	Structure Stability
ξ_{eq}	Equivalent Viscous damping
υ	Poisson's Ratio
ϕ	Diameter of bar
Φ_y	Yield curvature of pier

ABBREVIATIONS

BMRC	Bangalore Metro Rail Corporation
CP	Collapse Prevention
DCBG	Double Cell Box Girder
DDBD	Direct Displacement Based Design
DL	Dead Load
DRL	Derailment Load
EL	Construction & Erection Loads
EQ	Earthquake Loads
FBD	Force Based Design
FEMA	Federal Emergency Management Agency
IBC	International Building Code
IO	Immediate Occupancy
IS	Indian Standards
LL	Live Load or Imposed Loads
LS	Life Safety
OT	Temperature Loads
SCBG	Single Cell Box Girder
SIDL	Super Imposed Dead Loads
SR	Surcharge Loads (Traffic, building etc.)
TCBG	Triple Cell Box Girder
WL	Wind Loads

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

A metro system is an electric passenger railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. Metro System is used in cities, agglomerations, and metropolitan areas to transport large numbers of people at high frequency. The grade separation allows the metro to move freely, with fewer interruptions and at higher overall speeds. Metro systems are typically located in underground tunnels, elevated viaducts above street level or grade separated at ground level. An elevated metro structural system is more preferred one due to ease of construction and also it makes urban areas more accessible without any construction difficulty. An elevated metro structural system has the advantage that it is more economic than an underground metro system and the construction time is much shorter.

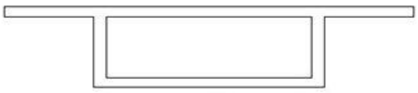
An elevated metro system has two major components pier and box girder. A typical elevated metro bridge model is shown in Figure 1.1 (a). Viaduct or box girder of a metro bridge requires pier to support the each span of the bridge and station structures. Piers are constructed in various cross sectional shapes like cylindrical, elliptical, square, rectangular and other forms. The piers considered for the present study are in rectangular cross section and it is located under station structure. A typical pier considered for the present study is shown in Figure 1.1 (b).

Box girders are used extensively in the construction of an elevated metro rail bridge and the use of horizontally curved in plan box girder bridges in modern metro rail systems is quite suitable in resisting torsional and warping effects induced by curvatures. The torsional and warping rigidity of box girder is due to the closed section of box girder. The box section also possesses high bending stiffness and there is an efficient use of the complete cross section. Box girder cross sections may take the form of single cell, multi spine or multi cell as shown in Figure 1.2.

(a) Typical Elevated Metro Bridge

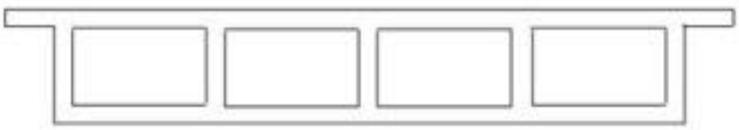
(b) Typical Pier

Figure 1.1: Typical Elevated Metro Bridge and its Elements



(a) Single Cell Box Girder

(b) Multi Spine Box Girder



(c) Multi Cell Box Girder

Figure 1.2: Types of Box Girder

1.2 SIGNIFICANCE OF THE STUDY

A force based seismic design approach is conventionally used to design the metro bridge pier. During a seismic loading, the behaviour of elevated bridges relies mostly on the ductility and the displacement capacity of the pier. It is important to check the ductility of such single piers. Force based methods do not explicitly check the displacement capacity at the design stage. The codes are now moving towards a performance-based (displacement-based) design approach, which consider the design as per the target performances at the design stage.

The behaviour of a box girder curved in plan is significantly different from a straight bridge and it is dependent on many parameters. A limited number of studies have been conducted on this aspect.

1.3 OBJECTIVE

- To study the performance of a pier designed by Force Based Design Method (FBD) and Direct Displacement Based Design (DDBD) Method.
- To study the parametric behaviour of a Curved Box Girder Bridges.

1.4 SCOPE

- The present study is limited to those practical cases that come across in an elevated metro project.
- With regard to the geometry of the pier considered, the present study is limited to
    - Rectangular pier cross section
    - Single pier structural system
    - Reinforced concrete pier
- Parametric Study on Box Girder is limited to,
    - Linear static and dynamic analysis and Nonlinear analysis is not considered
    - Rectangular box section with flanges.

- Reinforced concrete box girder section and not applicable to pre-stressed bridges.
- Single Cell and Multi Cell Box Girder and not applicable to Multi Spine box girder.
- Zero percentage gradient of the superstructure and super elevation is not considered in the modelling

1.4 ORGANIZATION OF THE THESIS

This thesis consists of five chapters. Chapter 1 gives the introduction about the present study which covers the significance, objective and scope of the study. Chapter 2 gives literature review which includes a method of design of the pier and parametric studies on box girder. Chapter 3 presents the performance study of a pier designed by Force Based Design Method and Direct Displacement Based Design Method. Chapter 4 describes the parametric study on the behaviour of curved box girder bridges. Chapter 5 presents summary and conclusion of the present study.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

To provide a detailed review of literature related to Metro bridge pier and Box Girder Bridge in its entirety is too immense to address in this thesis. However, there are many good references that can be used as a starting point for research. This literature review focuses on design of metro bridge pier and also review on research related to box girder bridges.

The literature review is divided into two segments. First segment deals with the design of the pier and the second part deals box girder. The first part of the chapter reviews Design of Metro Bridge Pier by Force Based Design (FBD) Method and Direct Displacement Based Seismic Design (DDBD) Method. The Second part of this chapter is focused on Box Girder Bridges and brief discussion on its research.

2.2 DESIGN OF PIER

Conventionally the pier of a metro bridge is designed using a force based approach. Recent studies (Priestley et al., 2007) show that the force based design may not necessarily guarantee the required target performances. The codes are now moving towards a performance-based design approach, which consider the design as per the target performances at the design stage. As the present study focus on the application of displacement based approaches to pier design, a brief introduction of the two methods, force-based and displacement based design is summarised in the following sections.

2.2.1 FORCE BASED DESIGN METHOD

Force Based Design Method (FBD) is the conventional method to design the metro bridge pier. In Force based design method, the fundamental time period of the structure is estimated from member elastic stiffnesses, which is estimated based on the assumed geometry of the section. The appropriate force reduction factor (R) corresponding to the assessed ductility capacity of the structural system and material is selected in the force based design and applied to the base shear of the structure.

The design of a pier by force based seismic design method is carried out as per IS 1893: 2002 Code. The design procedure to find the base shear of the pier by FBD method is summarized below.

Step 1: The structural geometry of the pier is assumed.

Step 2: Member elastic stiffness are estimated based on member size.

Step 3: The fundamental period is calculated by:

$$T = 0.075\, h^{0.75}$$

Where h = Height of Building, in m

Step 4: Seismic Weight of the building (W) is estimated.

Step 5: The design horizontal seismic coefficient A_h for a structure determined by

$$A_h = \frac{Z\, I\, S_a}{2\, R\, g}$$

Where, Z = Zone factor

I = Importance factor

R = Response reduction factor,

Sa/g = Average response acceleration coefficient

Z, I, R and Sa/g are calculated as per IS 1893:2002 Code.

Step 6: The total design lateral force or design seismic base shear force (V_B) along any principal direction is given by

$$V_B = A_h W$$

Where A_h = Design Horizontal Seismic Coefficient and

W= Seismic Weight of the Building

2.2.2 DIRECT DISPLACEMENT BASED DESIGN METHOD

The direct displacement based seismic design (DDBD) is proposed by Priestley et al. (2007) is used in the present study to design a metro bridge pier. The design philosophy of DDBD is based on the determination of the optimum structural strength to achieve a given performance limit state, related to a defined level of damage, under a specified level of seismic intensity., Priestley et al. (2007). The pier designed by DDBD method gives the uniform risk factor for the whole structure.

The design procedure to find the base shear of the pier by DDBD method is summarized below.

Step 1: Yield Curvature is calculated by

$$\Phi_y = (2.10 * \varepsilon_y)/h_c$$

Where, ε_y is the yield strain and

h_c is the section depth of rectangular column

Step 2: Yield Displacement is calculated by

$$\Delta_y = \Phi_y (H + L_{sp})^2 / 3$$

Where, H is the Column Height and

L_{sp} is the Effective additional height representing strain penetration effects

Step 3: Design Displacement is lesser of

$$\Delta_d = \theta_d * H \text{ or } \mu * \Delta_y$$

The ductility at design displacement is, $\mu = \Delta_d / \Delta_y$

Where, θ_d = Drift limit

Step 4: Equivalent viscous damping

$$\xi_{eq} = 0.05 + 0.444(\mu - 1/\mu\pi)$$

Step 5: Maximum spectral displacement is calculated from Design Displacement Spectra given in Priestley et al. (2007).

Step 6: Design Strength/Base Shear is given by

$$V_B = K_e \Delta_d$$

$$V_B = \left[\frac{4\pi^2 m_e}{T_e^2} . \frac{\Delta_{c,n}^2}{\Delta_d} . \left(\frac{0.07}{0.02 + \xi} \right) \right]^{2\alpha}$$

Where, K_e = Effective Stiffness at peak response

T_e = Effective response period of pier

ξ = Damping

$\Delta_{c,n}$ = Displacement at the corner period for n % damping

2.3 BOX GIRDER BRIDGES

In the past three decades, the finite element method of analysis has rapidly become popular and effective technique for the analysis of box girder bridges. So many researchers conducted studies on Box girder bridges by using finite element method. Khaled et al. (2001, 2002) have conducted detailed literature review on analysis of box girder bridges. Based on Khaled et al. (2001, 2002), the following literature review has been done and presented.

Malcolm and Redwood (1970) and Moffatt and Dowling (1975) studied the shear lag phenomena in steel box-girder bridges.

Sisodiya et al. (1970) approximated the curvilinear boundaries of finite elements used to model the curved box-girder bridges by a series of straight boundaries using parallelogram elements. This approximation would require a large number of elements to achieve a satisfactory solution. Such an approach is impractical, especially for highly curved box bridges.

Komatsu and Nakai (1966, 1970) presented several studies on the free vibration and forced vibration of horizontally curved single, and twin box-girder bridges using the fundamental equation of motion along with Vlasov’s thin-walled beam theory. Field tests on bridges excited either by a shaker or by a truck travelling at various speeds showed reasonable agreement between the theory and experimental results.

Chu and Pinjarkar (1971) proposed a finite element formulation of curved box-girder bridges, consisting of horizontal sector plates and vertical cylindrical shell elements. The method can be applied only to simply supported bridges without intermediate diaphragms.

Chapman et al. (1971) carried out a finite element analysis on steel and concrete box-girder bridges to study the effect of intermediate diaphragms on the warping and distortional stresses.

Lim et al. (1971) proposed an element that has a beam-like-in-plane displacement field. The element is trapezoidal in shape, and hence, can be used to analyse right, skew, or curved box-girder bridges with constant depth and width.

William and Scordelis (1972) presented an elastic analysis of cellular structures of constant depth with arbitrary geometry in the plane using quadrilateral elements.

Cheung and Cheung (1972) described the application of the finite-strip method for the determination of the natural frequencies and mode shapes of vibration of straight and curved beam-slab or box-girder bridges.

Tabba (1972) utilized the thin-walled beam theory to estimate the natural modes and frequencies of a curved simply supported girder of asymmetric multi cell section. Results from testing two curved cellular plexiglass models were used to verify the proposed method.

Fam (1973) studied the behaviour of curved box-girder bridges using the finite-element method for applied dynamic loads. Results from testing a single-cell plexiglass model having high curvature were used to verify the proposed method.

Armstrong and Landon (1973) and Greig and Armstrong (1973) reported the results of a field study of a curved twin-spine composite box-girder bridge in Springfield, Mass.

Bazant and El Nimeiri (1974) attributed the problems associated with the neglect of curvilinear boundaries in elements used to model curved box beams to the loss of continuity at the end cross sections of two adjunct elements meeting at an angle. They developed a skew-ended finite element with shear deformation using straight elements and adopted a more accurate theory that allows for transverse shear deformations.

Buchanan et al. (1974) conducted an experimental field investigation on the impact factor of a twin cell box-girder bridge with a composite deck near Baltimore.

Fam and Turkstra (1975) described a finite-element scheme for static and free-vibration analysis of box girders with orthogonal boundaries and arbitrary combinations of straight and horizontally curved sections using a four-node plate bending annular element with two straight radial boundaries, for the top and bottom flanges, and conical elements for the inclined web members.

Rabizadeh and Shore (1975) conducted a finite-element method for the dynamic analysis of curved multiple box-girder bridges, which formed the basis for the impact factor adopted by AASHTO (1980). The vehicle was simulated by two sets of concentrated forces having components in the radial and transverse directions, and moving with constant angular velocities on circumferential paths of the bridge.

Ramesh et al. (1976) uncoupled in-plane and out-of-plane forces and neglected shear deformation to introduce a curved element with 6 degrees of freedom at each node. Their method is applicable to single and multi-cell sections.

Moffat and Lim (1976) presented a finite-element technique to analyse straight composite box-girder bridges will complete or incomplete interaction with respect to the distribution of the shear connectors.

Chu and Jones (1976) extended the developed finite-element formulation of curved box-girder bridges (Chu and Pinjarkar 1971) to the dynamic analysis of such bridges.

Turkstra and Fam (1978) demonstrated the importance of warping and distortional stresses in a single-cell curved bridge, in relation to the longitudinal normal bending stresses obtained from curved beam theory.

Sargious et al. (1979) studied the behaviour of end diaphragm with opening in single-cell concrete box-girder bridges supported by a central pier.

Daniels et al. (1979) presented the results of a finite-element study concerning the effect of spacing of the rigid interior diaphragms on the fatigue strength of curved steel box girders. The results showed that reducing the interior diaphragms spacing effectively controls the distortional normal and bending stresses and increases the fatigue strength of curved steel box girders.

Jirousek and Bouberguig (1979) presented an efficient macro-element formulation for static analysis of curved box-girder bridges with variable cross section.

Templeman and Winterbottom (1979) used the finite-element method to investigate the minimum cost design of concrete spine box beam bridge decks.

Heins and Sahin (1979) evaluated the first natural frequency of straight and curved, simply supported and continuous, multispine box-girder bridges using a finite-difference technique to solve the differential equations of motion based on Vlasov's thin-walled beam theory.

Heins and Lee (1981) presented the experimental results obtained from vehicle-induced dynamic field testing of a two-span continuous curved composite concrete deck-steel single-cell bridge, located in Seoul.

Cheung et al. (1982) published results of experimental tests for moment impact factors for box girders with straight alignments.

Dezi (1985) examined the influence of some parameters on the deformation of the cross section in curved single-cell box beams over those in straight single-cell box beams. The parameters considered in this study were transverse and longitudinal locations of external loads, span-to-radius ratio, width-to-depth of the cell, and number of cross diaphragms.

Ishac and Smith (1985) presented simple design approximations for determining the transverse moments in single-span single-cell concrete box-girder bridges.

Mirza et al. (1985) and Cheung and Mirza (1986) investigated experimentally and theoretically, using the finite-element method, the influence of the bracing systems on the fundamental frequency of a composite concrete deck-steel twin box girder bridge model continuous over two spans, with a varying depth at the intermediate support.

Balendra and Shanmugam (1985) and Shanmugam and Balendra (1986) studied the free vibration response of straight multi cell structures with solid webs and with web openings.

Chang and Zheng (1987) used a finite-element technique to analyse the shear lag and negative shear lag effects in cantilever box girders. Expressions were derived to determine the region of negative shear lag effect with the interrelation of span and width parameters.

Inbanathan and Wieland (1987) presented an analytical investigation on the dynamic response of a simply supported box-girder bridge due to a vehicle moving over a rough deck.

Dilger et al. (1988) studied the effect of presence and orientation of diaphragms on the reaction, internal forces, and the behaviour of skew, single cell, concrete box-girder bridges.

Shushkewich (1988) showed that the actual 3D behaviour of a straight box-girder bridge, as predicted by a folded-plate, finite-strip, or finite-element analysis, can be approximated by using some simple membrane equations in conjunction with a plane frame analysis. In particular, the proposed method allows the reinforcing and prestressing to be proportional for transverse flexure, as well as the stirrups to be proportioned for longitudinal shear and torsion in single-cell, precast concrete, segmental box-girder bridges.

Mirza et al. (1990) conducted free-vibration tests on prestressed concrete simply supported one- and two-cell box-girder bridge models.

Galdos (1988), Galdos et al. (1993), and Schelling et al. (1992) studied the dynamic response of horizontally curved composite multi spine box-girder bridges of different spans, based on a planar grid finite-element analysis. The moving vehicle was represented by two constant forces with no mass, traveling with constant angular velocity in a circumferential path. Bridge damping was neglected. Their findings form the basis for the impact factors currently used by AASHTO (1993) for curved multi spine box-girder bridges.

Cheung and Li (1991) extended the application of the spline finite strip method to free-vibration analysis of curved box-girder bridges to reduce the computational effort when compared to the finite-element method.

Cheung and Megnounif (1991) conducted an analytical investigation using the finite-element method to study the influence of diaphragms, cross bracings, and bridge aspect ratio on the dynamic response of a straight twin box-girder bridge of 45 m span.

Mishra et al. (1992) presented an investigation into the use of closely associated finite-difference technique for the analysis of right box-girder bridges as a feasible alternative to the finite element method. The method discretizes the total energy of the structure into energy due to extension and bending and that due to shear and twisting contributed by two separate sets of rectangular elements formed by a suitable finite-difference network.

Kashif (1992) developed a finite-element technique to analyse the dynamic response of simply supported multiple box-girder bridges considering vehicle- bridge interaction.

Kou et al. (1992) presented a theory that incorporates a special treatment of warping in the free-vibration analysis of continuous curved thin-walled girder bridges. Also, Kou (1989) examined the dynamic response of curved continuous box girder bridges.

Galuta and Cheung (1995) developed a hybrid analytical solution that combines the boundary element method with the finite-element method to analyse box-girder bridges. The finite-element method was used to model the webs and bottom slab of the bridge, while the boundary element method was employed to model the top slab.

Jeon et al. (1995) presented a procedure for static and dynamic analysis of composite box beams using a large deflection beam theory. The finite-element equations of motion for beams undergoing arbitrary large displacements and rotations, but small strains, were obtained from Hamilton’s principle.

Fafitis and Rong (1995) presented a sub structuring analysis method for thin walled box girders. In this method, instead of solving the condensed equilibrium equations in the traditional sub structuring method, a mix of compatibility and equilibrium equations are employed with shear forces at the interfaces of thin walls as major unknowns. The proposed method can be performed using any commercial finite-element analysis software.

Huang et al. (1995) presented a procedure for obtaining the dynamic response of thin-walled box-girder bridges due to truck loading over a rough road surface, based on a thin-walled beam finite-element model considering warping torsion and distortion. Later, this procedure was extended (Wang et al. 1996) to study the free-vibration characteristics and the dynamic response of three-span continuous and cantilever thin-walled single-cell box-girder bridges when subjected to multivehicle load moving across a rough bridge deck. Most recently, this procedure was also extended (Huang et al. 1998) to curved box-girder bridges to obtain their impact factor characteristics.

Abdelfattah (1997) utilized 3D finite-element modelling to study the efficiency of different systems for stiffening steel box girders against shear lag.

Senthilvasan et al. (1997) combined the spline finite-strip method of analysis and a horizontally curved folded-plate model to investigate the bridge-vehicle interaction in curved single- and multi cell bridges.

Sennah and Kennedy (1997, 1998c) conducted indepth studies on the free vibration response of simply supported and continuous curved composite cellular box-girder bridges, resulting in empirical expressions for the dominant frequency for such bridges.

Samaan et al. (2007) presented a dynamic analysis of curved continuous multiple box girder bridges, using the finite element method, to evaluate their natural frequencies and mode shapes and experimental tests are conducted on two continuous twin-box girder bridge models of different curvatures to substantiate the finite-element model.

Gupta et al. (2010) conducted a detailed study of box girder bridge cross-sections namely Rectangular, Trapezoidal and Circular and also presented a parametric study for deflections, longitudinal and transverse bending stresses and shear lag for all cross-sections.

2.4 SUMMARY

This chapter reviewed the literature regarding the two major elements of an elevated bridge. First segment dealt with the design of the pier and second part dealt with the box girder. The first part of the chapter reviewed Design of Metro Bridge Pier by Force Based Design (FBD) Method and Direct Displacement Based Seismic Design (DDBD) Method.

The Second part of this chapter is focused on Box Girder Bridges and brief discussion on its research. Based on the critical assessment of literature of box girder, it can be concluded that box girder bridges can be analysed by using finite element method and there are only limited numbers of parametric studies are available on curved in plan box girder bridges by considering all the parameters. So it is necessary to carry out the parametric study on curved box girder bridges to know the response parameters.

CHAPTER 3

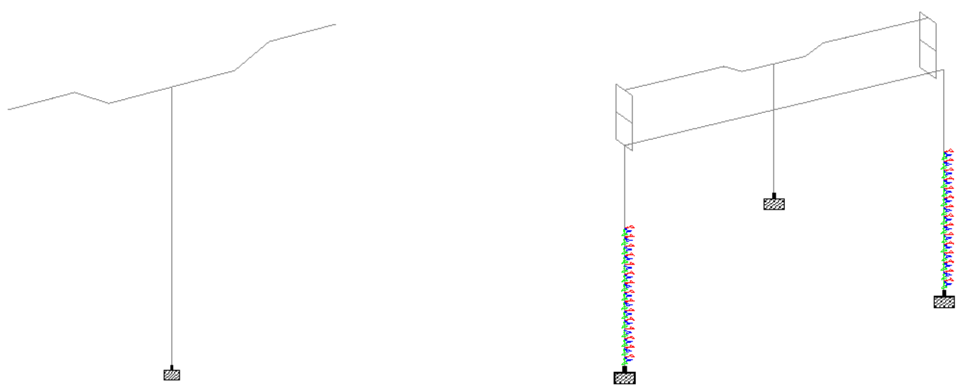
PERFORMANCE STUDY OF A PIER DESIGNED BY FBD AND DDBD

3.1 OVERVIEW

Performance study of the typical pier designed by a Force Based Design (FBD) Method and Direct Displacement Based Design (DDBD) Method is described in this chapter. The pier is designed based on FBD and DDBD Method. Performance assessment is carried out for the designed pier and the results are discussed briefly.

3.2 DESIGN OF PIER USING FORCE BASED DESIGN

The geometry of pier considered for the present study is based on the design basis report of the Bangalore Metro Rail Corporation (BMRC) Limited. The piers considered for the analysis are located in the elevated metro station structure. The effective height of the considered piers is 13.8 m. The piers are located in Seismic Zone II, as per IS 1893 (Part 1): 2002. The modelling and seismic analysis is carried out using the finite element software STAAD Pro. The typical pier models considered for the present study are shown in figure 3.1.



(Type A) (Type B)

Figure 3.1: Typical Pier Model

3.2.1 Material Property

The material property considered for the present pier analysis for concrete and reinforcement steel are given in Table 3.1.

Table 3.1: Material Property for Pier

Properties of Concrete	
Compressive Strength of Concrete	60 N/mm^2
Density of Reinforced Concrete	24 kN/m^3
Elastic Modulus of Concrete	36000 N/mm^2
Poisson's Ratio	0.15
Thermal Expansion Coefficient	1.17×10^{-5} $/^0C$
Properties of Reinforcing Steel	
Yield Strength of Steel	500 N/mm^2
Young's Modulus of Steel	205,000 N/mm^2
Density of Steel	78.5 kN/m^3
Poisson's Ratio	0.30
Thermal Expansion Coefficient	1.2×10^{-5} $/^0C$

3.2.2 Design Load

The elementary design load considered for the analysis are Dead Loads (DL), Super Imposed Loads (SIDL), Imposed Loads (LL), Earthquake Loads (EQ), Wind Loads (WL), Derailment Load (DRL), Construction & Erection Loads (EL), Temperature Loads (OT) and Surcharge Loads (Traffic, building etc.) (SR). The approximate loads considered for the analysis are shown in Table 3.2. The total seismic weight of the pier is 17862 kN.

Table 3.2: Approximate design Load

Load from Platform Level	**Load**	**Load from Track Level**	**Load**
Self Weight	120 kN	Self Weight	160 kN
Slab Weight	85 kN	Slab Weight	100 kN
Roof Weight	125 kN	**Total DL**	260 kN
Total DL	330 kN	SIDL	110 kN
SIDL	155 kN	**Train Load**	190 kN
Crowd Load	80 kN	Braking + Tractive Load	29 kN
LL on Roof	160 kN	Long Welded Rail Forces	58 kN
Total LL	240 kN	Bearing Load	20 kN
Roof Wind Load	85 kN	**Temperature Load**	
Lateral	245 kN	For Track Girder	20 kN
Bearing Load	14 kN	For Platform Girder	14 kN
		Derailment Load	80 kN/m

The force based design is carried out for Pier as per IS 1893:2002 and IRS CBC 1997 Code and the results are shown in Table 3.3. From the FBD, it is found out that the minimum required cross section of the pier is only 1.5 m x 0.7 m for 2 % reinforcement. The base shear of the pier is 891 kN.

Table 3.3: Reinforcement Details as per Force Based Design

Pier Type	**Cross Section (m)**	**Diameter of Bar (mm)**	**Number of Bars**	**% of Reinforcement**	
				Required	**Provided by BMRC**
Pier Type A	2.4 x 1.6	32	#32	0.8 %	1.48 %
Pier Type B	2.4 x 1.6	32	#38	0.8 %	1.48 %

3.3 DESIGN OF PIER USING DIRECT DISPLACEMENT BASED DESIGN

The direct displacement based seismic design method proposed by Priestley et al. (2007) and IRS CBC 1997 Code is used to design of Pier Type B and the results are shown in Table 3.4. The performance level considered for the study is a Life Safety (LS) level.

Table 3.4 Reinforcement Details as per Direct Displacement Based Seismic Design

Displacement Ductility	Drift Limit (m)	Cross Section (m)	Base Shear V_b (kN)	Diameter of Bar (mm)	Number of Bars	% of Reinforcement Required
1	0.276	1.5 x 0.7	604	32	#16	1.2 %
2	0.276	1.5 x 0.7	150	32	#12	0.8 %
3	0.276	1.5 x 0.7	86	32	#12	0.8 %
4	0.276	1.5 x 0.7	60	32	#12	0.8 %

The parametric study is carried to know the effect of displacement ductility on base shear for different Performance levels and the results are shown in Figure 3.2. The figure shows that as the displacement ductility level increases the base shear of the pier decreases and also the difference between different performance levels is about 40 %.

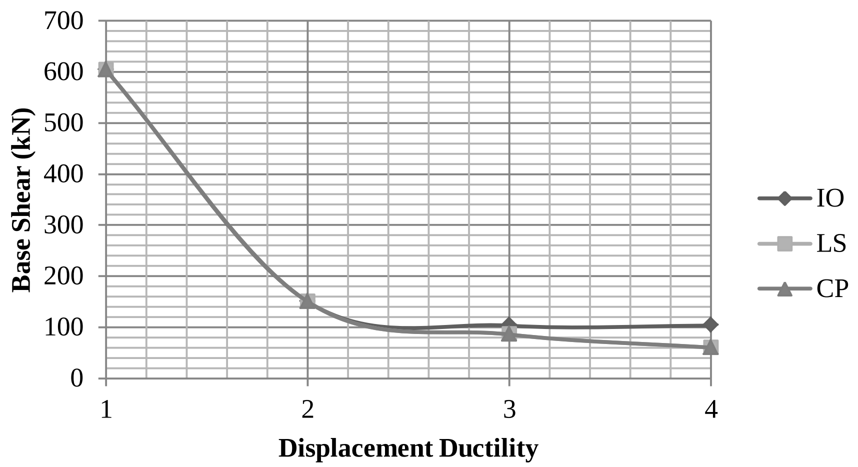


Figure 3.2: Effect of displacement ductility on base shear for different Performance levels

3.4 PERFORMANCE ASSESSMENT

The performance assessment is done to study the performance of designed pier by Force Based Design Method and Direct Displacement Based Design Method. For this purpose, Non-linear static analysis is conducted for the designed pier using SeismoStruct Software and the results are shown in Table 3.5. The section considered is 1.5 m x 0.7 m. Performance parameters behaviour factor (R´), structure ductility (μ’) and maximum structural drift (Δ'_{max}) are found for both the cases.

The behaviour factor (R´) is the ratio of the strength required to maintain the structure elastic to the inelastic design strength of the structure. The behaviour factor, R´, therefore accounts for the inherent ductility, over the strength of a structure and difference in the level of stresses considered in its design. FEMA 273 (1997), IBC (2003) suggests the R factor in force-based seismic design procedures. It is generally expressed in the following form taking into account the above three components,

$$R' = R_{\mu} \bullet R_{s} \bullet Y$$

$$R_{\mu} = \frac{V_e}{V_y}, R_s = \frac{V_y}{V_s}, Y = \frac{V_s}{V_w}$$

where, R_{μ} is the ductility dependent component also known as the ductility reduction factor, R_S is the over-strength factor and Y is termed the allowable stress factor. With reference to Figure 3.3, in which the actual force–displacement response curve is idealised by a bilinear elastic–perfectly plastic response curve, the behaviour factor parameters may be defined as

$$R'(R_w) = \left(\frac{V_e}{V_y}\right)\left(\frac{V_y}{V_s}\right)\left(\frac{V_s}{V_w}\right) = \frac{V_e}{V_w}$$

where, V_e, V_y, V_s and V_w correspond to the structure's elastic response strength, the idealised yield strength, the first significant yield strength and the allowable stress design strength, respectively as shown in the Figure 3.3.

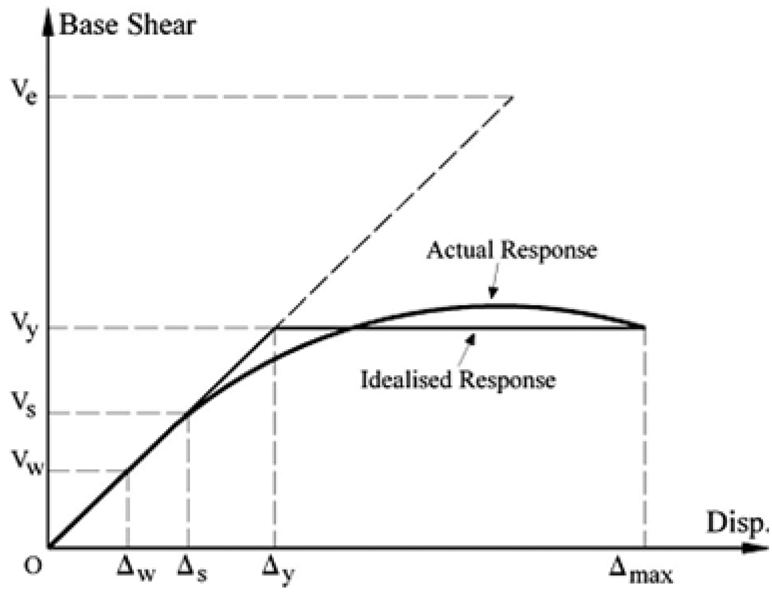


Figure 3.3: Typical Pushover response curve for evaluation of performance parameters

The structure ductility, μ', is defined in as maximum structural drift (Δ'_{max}) and the displacement corresponding to the idealised yield strength (Δ_y) as:

$$\mu' = \frac{\Delta'_{max}}{\Delta_y}$$

In Force Based Design, a force reduction factor (R) of 2.5 is used, and the design base shear is estimated to be 891kN in the FBD. The performance parameters of the section designed using FBD shows that the behaviour factor R is found to be about 2.74. The same pier is designed using a DDBD method for target displacement ductility and drift, the performance parameters structural ductility and structural drift are found out for these cases. It shows that the achieved performance parameters are higher than assumed in the design stage in both cases of DDBD. Though the FBD may not always guarantee the performance parameter required, in the present case the pier achieves the target requirement. In the case of DDBD, the design considers the target displacement ductility and drift at the design stage, and the present study shows that in both the examples the DDBD method achieves the behaviour factors more than targeted Values. These conclusions can be considered only for the selected pier. For General conclusions large number of case studies is required and it is treated as a scope of future work.

Table 3.5: Performance Assessment of designed Pier

Designed			**Type of design**	**V_b (kN)**	**% of Steel**	**Φ (mm)**	**No. of Bars**	**Performance Parameters Achieved**		
μ	**Δ**	**R**						**μ**	**Δ**	**R**
		2.5	FBD	891	2 %	32	#28			2.74
1	0.276		DBD	604	1.2 %	32	#16	3.5	0.35	3.25
2	0.276		DBD	150	0.8 %	32	#12	3.4	0.34	11.63

3.5 SUMMARY

In this chapter the performance study on designed pier by FBD and DDBD is carried out. The design of the pier is done by both forced based design method and direct displacement based design method. The parametric study showed that the effect of displacement ductility on base shear for different Performance levels. The performance assessment of selected designed pier showed that, FBD Method may not always guarantee the performance parameter required and in the present case the pier just achieved the target requirement. In case of DDBD method, selected pier achieved the behaviour factors more than targeted Values. These conclusions can be considered only for the selected pier.

CHAPTER 4

PARAMETRIC STUDY ON BEHAVIOUR OF CURVED BOX GIRDER BRIDGES

4.1 OVERVIEW

Parametric study of box girder bridges using finite element method is described in this chapter. The parameters of box girder bridges considered in this study are radius of curvature, span length, span length to the radius of curvature ratio and number of boxes. The various responses parameters considered are the longitudinal stress at the top and bottom, shear, torsion, moment, deflection and fundamental frequency.

Numerical analysis carried out by Gupta et al. (2010) is used for validation of the finite element model. The parametric study is carried out, using 60 bridge models, to investigate the behaviour of box girder bridges. Also, the results obtained from parametric study are discussed briefly in this chapter.

4.2 VALIDATION OF THE FINITE ELEMENT MODEL

To validate the finite element model of box girder bridges in SAP 2000, a numerical example from the literature (Gupta et al., 2010) is considered. Figure 4.1 shows the cross section of simply supported Box Girder Bridge considered for validation of finite element model. Box girder considered is subjected to two concentrated loads (P = 2 X 800 N) at the two webs of mid span. Span Length assumed in this study is 800 mm and the material property considered are Modulus of elasticity (E) =2. 842GPa and Modulus of rigidity (G) =1. 015GPa.

The mid span deflection of the modelled box girder bridge is compared with the literature and it is presented in the Table 4.1. From the Table 4.1, it can be concluded that the present model gives the accurate result.

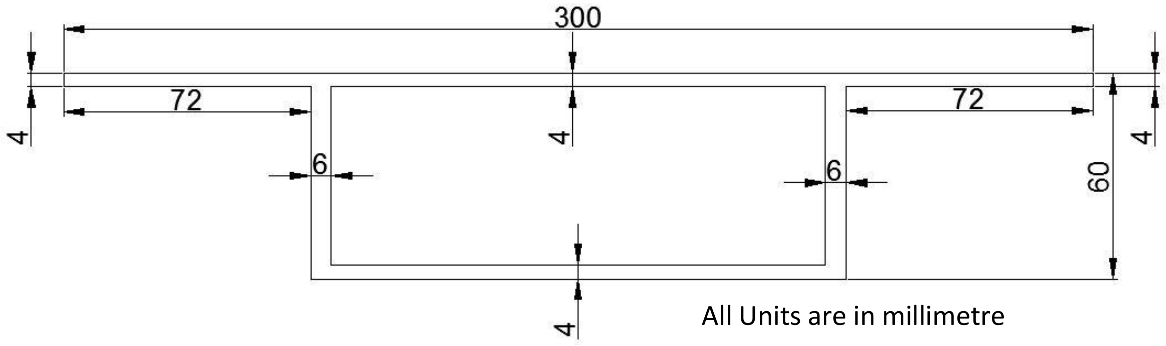


Figure 4.1: Cross Section of Simply Supported Box Girder Bridge

Table 4.1: Mid Span Deflection of Simply Supported Box Girder Bridge

Parameter	Gupta et al. (2010)	Present Study
Mid Span Deflection (mm)	4.92	4.91

4.3 CASE STUDY OF BOX GIRDER BRIDGES

The geometry of Box Girder Bridge considered in the present study is based on the design basis report of the Bangalore Metro Rail Corporation (BMRC) Limited. In this study, 60 numbers of simply supported box girder bridge model is considered for analysis to study the behaviour of box girder bridges. The details of the cross section considered for this study is given in Figure 4.2 and various geometric cases considered for this study are presented in Table 4.2. The material property considered for the present study is shown in Table 4.3.

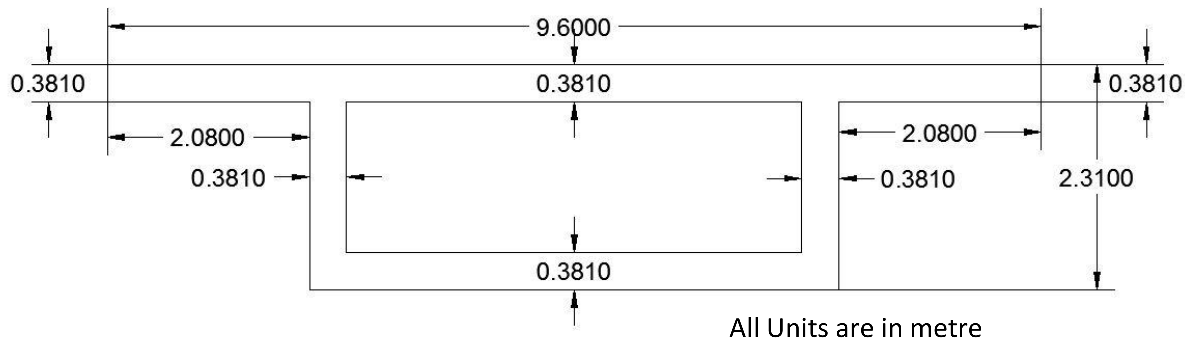


Figure 4.2: Cross Section of Simply Supported Box Girder Bridge considered for study

Table 4.2: Geometries of Bridges used in Parametric Study

Span Length (m)	Radius of Curvature (m)	Theta (radian)	Number of Boxes
Radius of Curvature			
31	∞	0.0000	1,2,3
31	100	0.3100	
31	150	0.2067	
31	200	0.1550	
31	250	0.1240	
31	300	0.1033	
31	350	0.0886	
31	400	0.0775	
Span Length			
16	120	0.1333	1,2,3
19	120	0.1583	
22	120	0.1833	
25	120	0.2083	
28	120	0.2333	
31	120	0.2583	
Span Length to Radius of Curvature Ratio			
12	120	0.1000	1,2,3
24	120	0.2000	
36	120	0.3000	
48	120	0.4000	
60	120	0.5000	
72	120	0.6000	

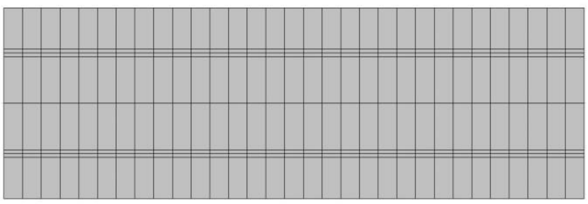
Table 4.3: Material Properties

Properties of Material	Value
Weight per unit volume	235400 N/m^3
Mass per unit volume	24000 N/m^3
Modulus of Elasticity (E)	32500×10^6 N/m^2
Poisson's Ratio (υ)	0.15
Coefficient of thermal expansion (A)	1.170×10^{-5} / °C
Shear Modulus (G)	1.413×10^{10} N/m^2
Specific Concrete Compressive Strength (f_c')	$45 \times 10^6 N/m^2$

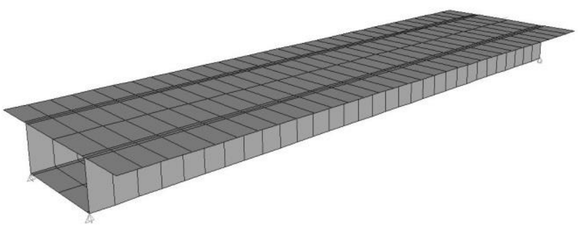
The moving load analysis is performed for live load of two lane IRC 6 Class A (Tracked Vehicle) loading for all the cases considered by using SAP 2000. The longitudinal stress at the top and bottom, shear, torsion, moment, deflection and fundamental frequency is calculated and compared with Single Cell Box Girder (SCBG), Double Cell Box Girder (DCBG) and Triple Cell Box Girder (TCBG) bridge cases for various parameters viz., radius of curvature, span length, and span length to the radius of curvature ratio.

4.4 FINITE ELEMENT MODELLING

The finite element modelling methodology adopted for validation study is used for the present study. The modelling of Box Girder Bridge is carried out using Bridge Module in SAP 2000. The Shell element is used in this finite element model to discretize the bridge cross section. At each node it has six degrees of freedom: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. The typical finite element discretized model of straight and curved simply supported box Girder Bridge in SAP 2000 is shown in figure 4.3(a) and 4.3(b).

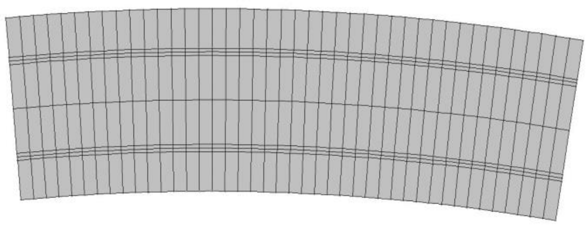


Plan

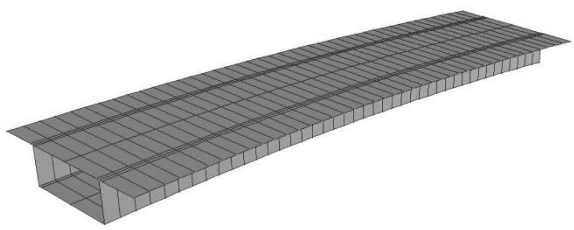


3D Model

Figure 4.3(a): Discretized model of simply supported Straight Box Girder Bridge in SAP 2000



Plan



3D Model

Figure 4.3(b): Discretized model of simply supported Curved Box Girder Bridge in SAP 2000

4.5 PARAMETRIC STUDY

The parametric study is carried out to investigate the behaviour (i.e., the longitudinal stress at the top and bottom, shear, torsion, moment, deflection and fundamental frequency) of box girder bridges for different parameters viz. radius of curvature, span length, span length to radius of curvature ratio and number of boxes.

4.5.1 Radius of Curvature

Two lane 31 m Single Cell Box Girder (SCBG), Double Cell Box Girder (DCBG) and Triple Cell Box Girder (TCBG) Bridge are analysed for different radius of curvatures to illustrate the variation of longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency with radius of curvature of box girder bridges.

To express the behaviour of box girder bridges curved in plan with reference to straight one, a parameter α is introduced. α is defined as the ratio of response of the curved box girder to the straight box girder.

The variation of longitudinal stress at top with radius of curvature of box girder bridges is shown in Figure 4.4. As the radius of curvature increases, the longitudinal stress at the top side of the cross section decreases for each type of Box Girder Bridge. Variation of Stress between radius of curvature 100 m and 400 m is only about 2 % and it is same for all the three cases. Stress variation between each type of box girder is only about 1 %. Figure 4.5 represents a non-dimensional form of the stress variation for all the three types of box girder. It shows that stress variation pattern is same for all the three types of box girder.

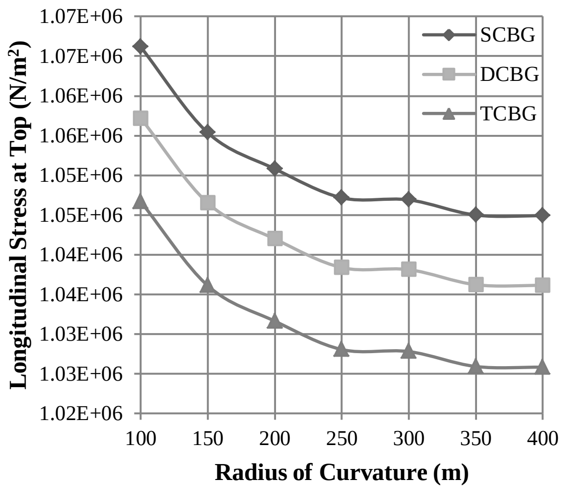


Figure 4.4: Variation of Longitudinal Stress with Radius of Curvature at Top of Box Girder

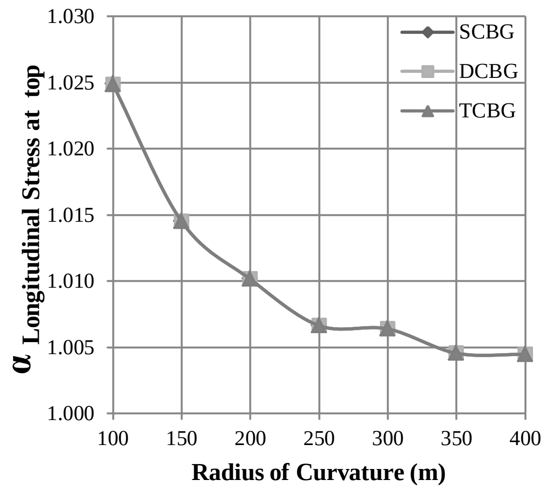


Figure 4.5: Variation of $\alpha_{\text{Longitudinal Stress at top}}$ with Radius of Curvature of Box Girder

The variation of longitudinal stress at the bottom with radius of curvature of box girder bridges is shown in Figure 4.6. As the radius of curvature increases, the longitudinal stress at the bottom side of the cross section decreases for each type of Box Girder Bridge. Variation of stress between radius of curvature 100 m and 400 m is only about 2 % and it is same for all the three cases. Variation of stress between each type of box girder is about 4 %. Figure 4.7 represents the non-dimensional form of the stress variation for all the three types of box girder. It shows that stress variation pattern is same for all the three types of box girder.

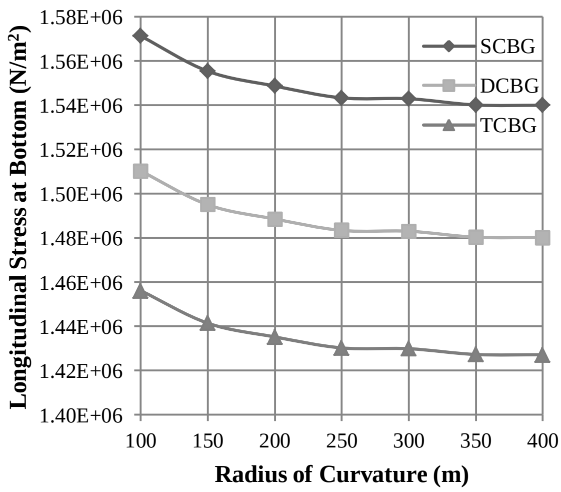


Figure 4.6: Variation of Longitudinal Stress with Radius of Curvature at Bottom of Box Girder

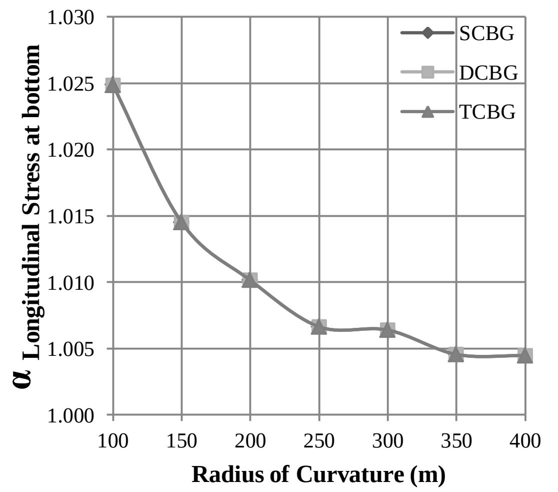


Figure 4.7: Variation of $\alpha_{\text{Longitudinal Stress at bottom}}$ with Radius of Curvature of Box Girder

The variation of shear force on the radius of box girder bridges is shown in Figure 4.8. As the radius of curvature increases, the shear force of box girder bridge decreases till radius of curvature 250 m and then it is having a slight increase up to 300 m and then decreases from a radius of curvature 300 m for each type of Box Girder Bridge. Variation of shear force between radius of curvature 250 m and 300 m is only about 0.07 % and it is same for all the three cases. Variation of shear force between radius of curvature 100 m and 400 m for each type of box girder is only about 0.7 %. Figure 4.9 represents the non-dimensional form of the shear force variation for all the three types of box girder. It shows that the shear force variation pattern is almost same for DCBG and TCBG and for SCBG; it is 1 % more than DCBG and TCBG.

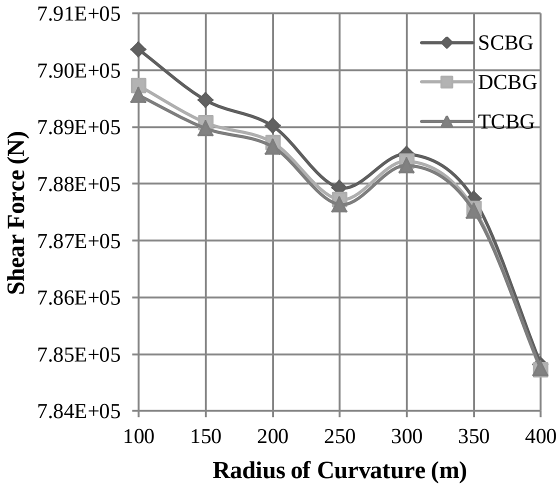


Figure 4.8: Variation of Shear Force with Radius of Curvature of Box Girder

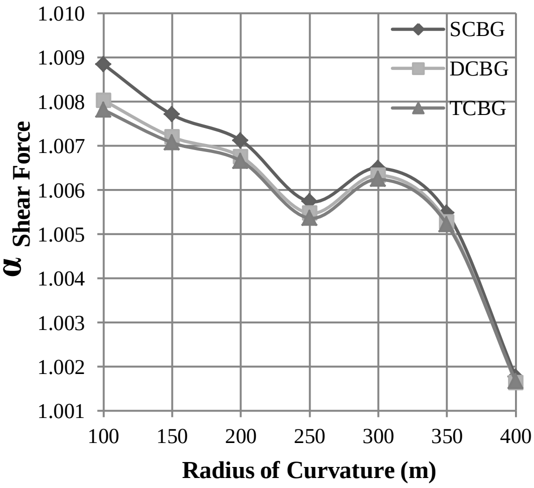


Figure 4.9: Variation of $\alpha_{\text{Shear Force}}$ with Radius of Curvature of Box Girder

The variation of torsion with radius of curvature of box girder bridges is shown in Figure 4.10. As the radius of curvature increases, torsion decreases for each type of Box Girder Bridge. Variation of torsion between radius of curvature 100 m and 400 m is about 16-19 % for all the three cases and it shows that the radius of curvature having a significant effect in torsion of box girder bridges. Variation of torsion between DCBG and TCBG is very small and variation of torsion between SCBG and others is about 3 %. Figure 4.11 represents a non-dimensional form of the torsion variation for all the three types of box girder. It shows that torsion variation pattern is same and has 3 % variation between the three types of box girder.

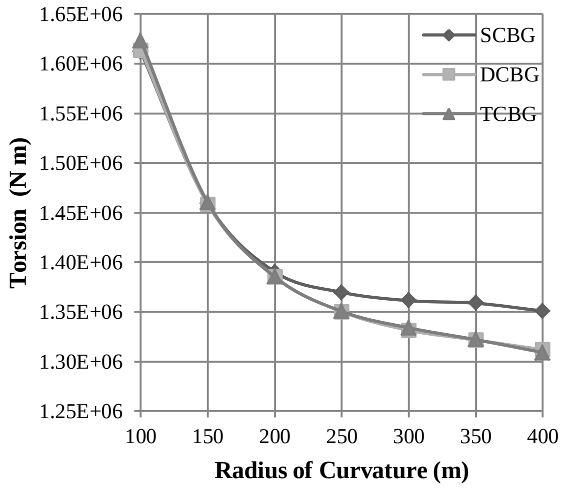


Figure 4.10: Variation of Torsion with Radius of Curvature of Box Girder

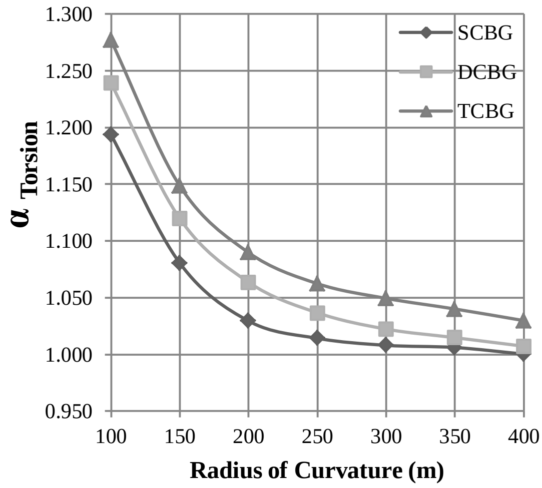


Figure 4.11: Variation of **α** $_{\text{Torsion}}$ with Radius of Curvature of Box Girder

The variation of moment with radius of curvature of box girder bridges is shown in Figure 4.12. As the radius of curvature increases, moment decreases for each type of Box Girder Bridge. Variation of moment between radius of curvature 100 m and 400 m is about 2 % for all the three cases. Variation of the moment is very small between three types of box girder. Figure 4.13 represents a non-dimensional form of the moment variation for all the three types of box girder. It shows that moment variation pattern is same between the three types of box girder.

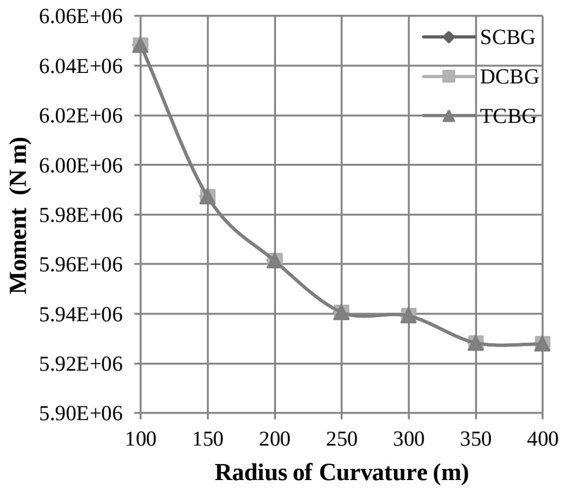


Figure 4.12: Variation of Moment with Radius of Curvature of Box Girder

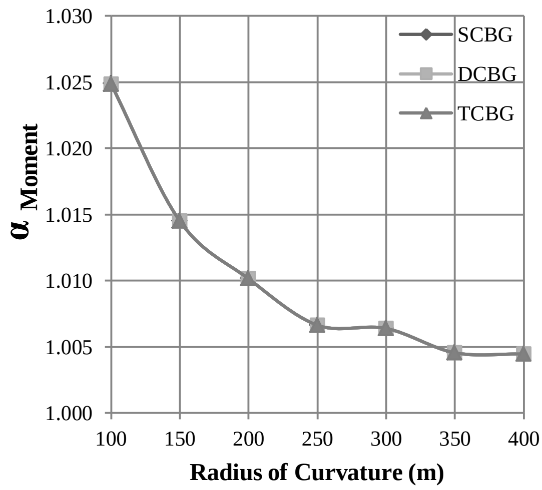


Figure 4.13: Variation of **α** $_{\text{Moment}}$ with Radius of Curvature of Box Girder

The variation of deflection with radius of curvature of box girder bridges is shown in Figure 4.14. As the radius of curvature increases, deflection decreases for each type of Box Girder Bridge. Variation of deflection between radius of curvature 100 m and 400 m is about 13-18 % for all the three cases. Variation of deflection between three types of box girder is about 15 % and this indicates that the effect of radius of curvature on deflection is significant. Figure 4.15 represents a non-dimensional form of the deflection variation for all the three types of box girder. It shows that the deflection variation pattern is same between the three types of box girder and has a variation of about 5 %.

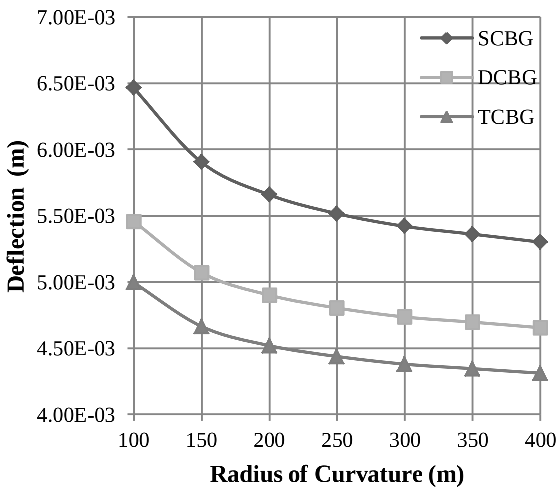


Figure 4.14: Variation of Deflection with Radius of Curvature of Box Girder

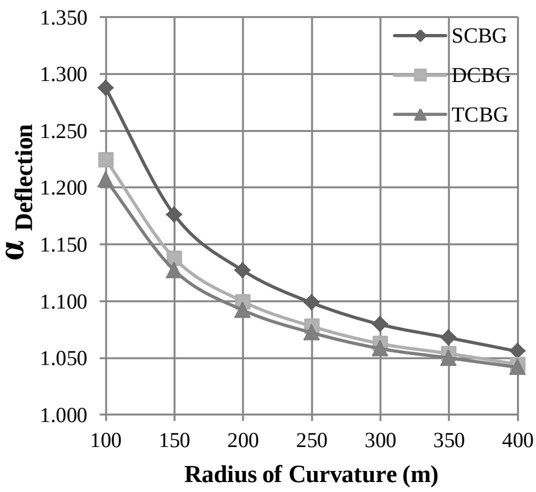


Figure 4.15: Variation of $\alpha_{\text{Deflection}}$ with Radius of Curvature of Box Girder

The variation of frequency with radius of curvature of box girder bridges is shown in Figure 4.16. As the radius of curvature increases, the variation of frequency is almost same for all the three cases of Box Girder Bridge. Variation of frequency between three types of box girder is only about 1%. This is due to the same span length. Figure 4.17 represents a non-dimensional form of the frequency variation for all the three types of box girder. It shows that frequency variation pattern is same between the three types of box girder and has a variation is only about 0.5 %.

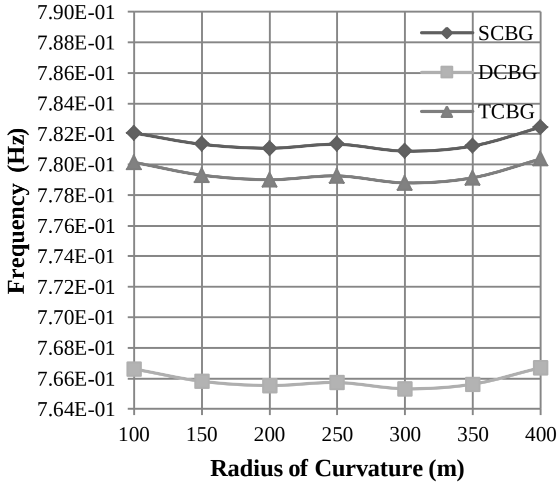


Figure 4.16: Variation of Natural Frequency with Radius of Curvature of Box Girder

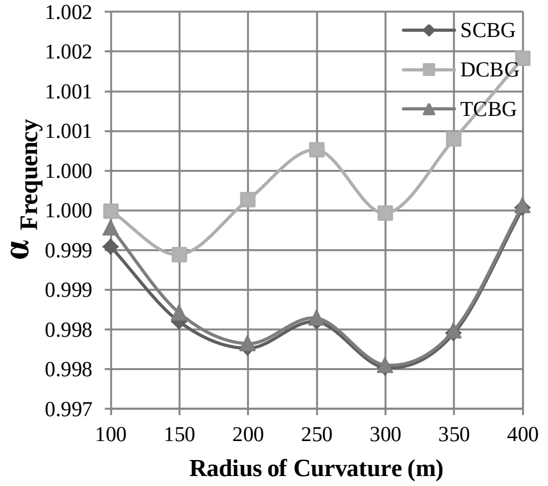


Figure 4.17: Variation of **α** $_{\text{Frequency}}$ with Radius of Curvature of Box Girder

4.5.2 Span Length

Two lanes with 120 m radius of curvature Single Cell Box Girder Bridge (SCBG), Double Cell Box Girder Bridge (DCBG) and Triple Cell Box Girder Bridge (TCBG) are analysed for different span length to illustrate the variation of longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency with a span length of box girder bridges.

The variation of Longitudinal Stress at the top with a span length of box girder bridges is shown in Figure 4.18. As the span length increases, longitudinal stress at top of box girder increases for each type of Box Girder Bridge. Variation of longitudinal stress at top of box girder between span length 16 m and 31 m is about 64 % for all the three cases and it shows that effect of span length on longitudinal stress at top is significant. Variation of longitudinal stress at top between three types of box girder is only about 2 %.

The variation of Longitudinal Stress at the bottom with a span length of box girder bridges is shown in Figure 4.19. As the span length increases, longitudinal stress at bottom of box girder increases for each type of Box Girder Bridge. Variation of longitudinal stress at bottom of box girder between span length 16 m and 31 m is about 64 % for all the three cases and it shows that effect of span length on longitudinal stress at the bottom is also significant. Variation of longitudinal stress at bottom between three types of box girder is about 5 %.

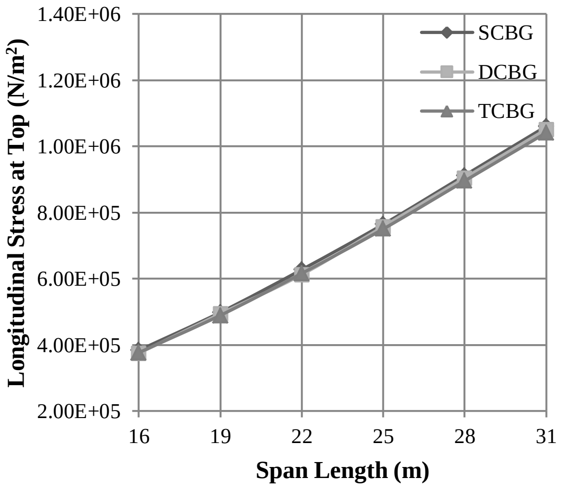


Figure 4.18: Variation of Longitudinal Stress at top with Span Length at Top of Box Girder

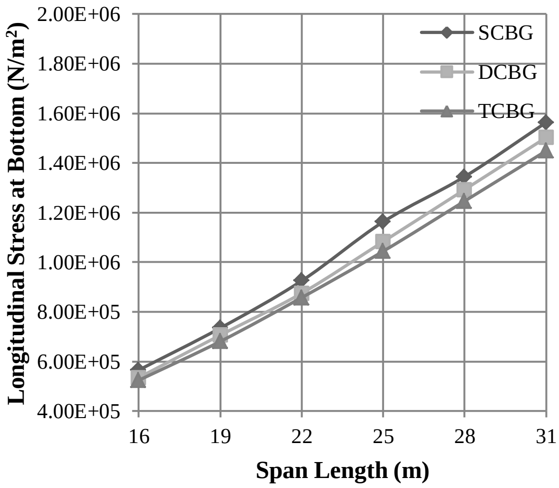


Figure 4.19: Variation of Longitudinal Stress at bottom with Span Length at Bottom of Box Girder

The variation of shear force with a span length of box girder bridges is shown in Figure 4.20. As the span length increases, Shear Force of box girder increases for each type of Box Girder Bridge. Variation of the shear force of box girder between span length 16 m and 31 m is about 25 % for all the three cases and it shows that effect of span length on shear force is significant. Variation of shear force between three types of box girder is about 5 %.

The variation of torsion with span length of box girder bridges is shown in Figure 4.21. As the span length increases, torsion of box girder increases for each type of Box Girder Bridge. Variation of torsion of box girder between span length 16 m and 31 m is about 32 % for all the three cases and it shows that effect of span length on torsion is significant. Variation of torsion between three types of box girder is only about 0.8 %.

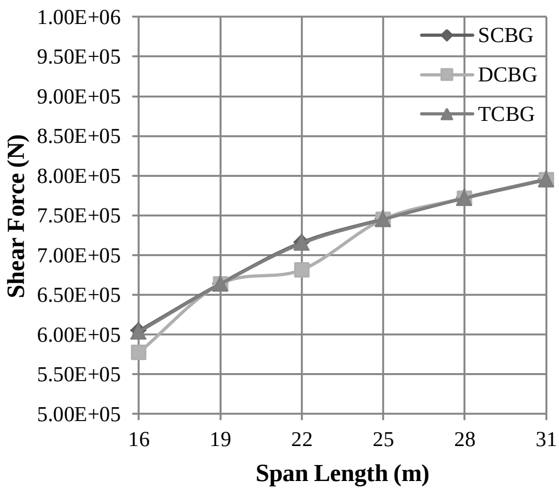


Figure 4.20: Variation of Shear Force with Span Length of Box Girder

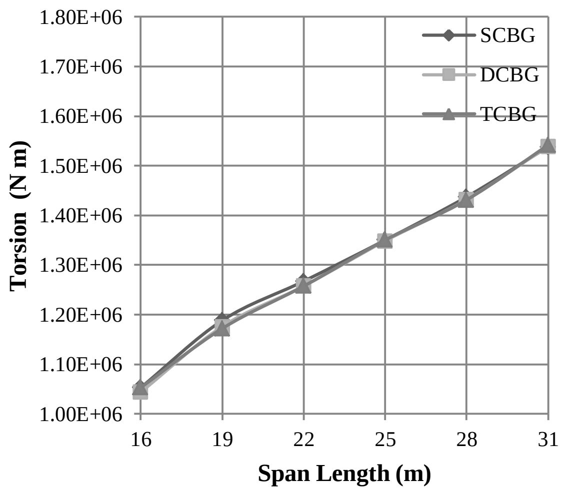


Figure 4.21: Variation of Torsion with Span Length of Box Girder

The variation of moment with a span length of box girder bridges is shown in Figure 4.22. As the span length increases, moment of box girder increases for each type of Box Girder Bridge. Variation of moment of box girder between span length 16 m and 31 m is about 64 % for all the three cases and it shows that effect of span length on the moment is significant. Variation of moment between three types of box girder is only about 1.5 %.

The variation of deflection with a span length of box girder bridges is shown in Figure 4.23. As the span length increases, deflection of box girder increases for each type of Box Girder Bridge. Variation of deflection of box girder between span length 16 m and 31 m is about 75 % for all the three cases and it shows that effect of span length on deflection is significant. Variation of deflection between three types of box girder is about 13 %.

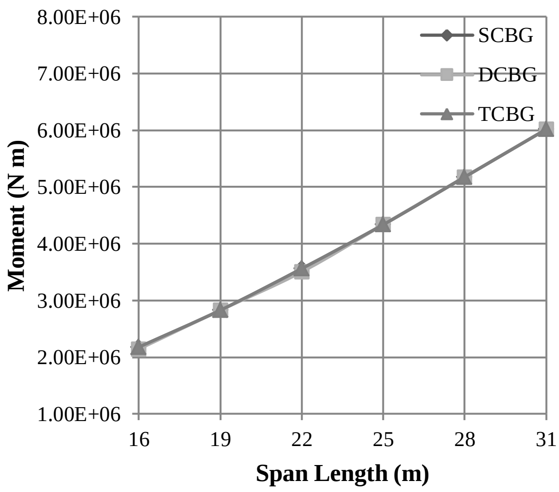


Figure 4.22: Variation of Moment with Span Length of Box Girder

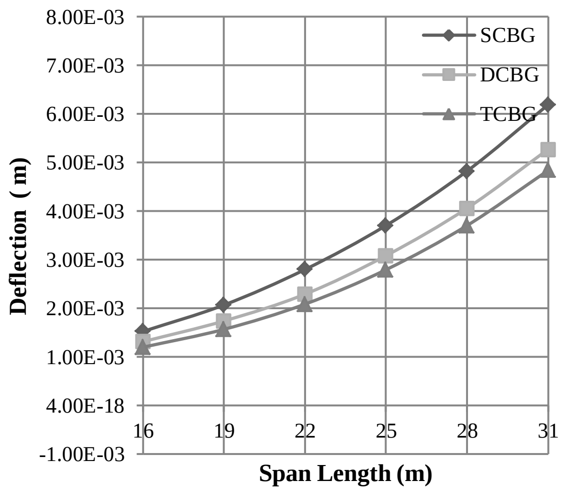


Figure 4.23: Variation of Deflection with Span Length of Box Girder

The variation of frequency with a span length of box girder bridges is shown in Figure 4.24. As the span length increases, frequency of box girder decreases for each type of Box Girder Bridge. Variation of frequency of box girder between span length 16 m and 31 m is about 66 % for all the three cases and it shows that effect of span length on frequency is significant. Variation of frequency between three types of box girder is only about 2 %.

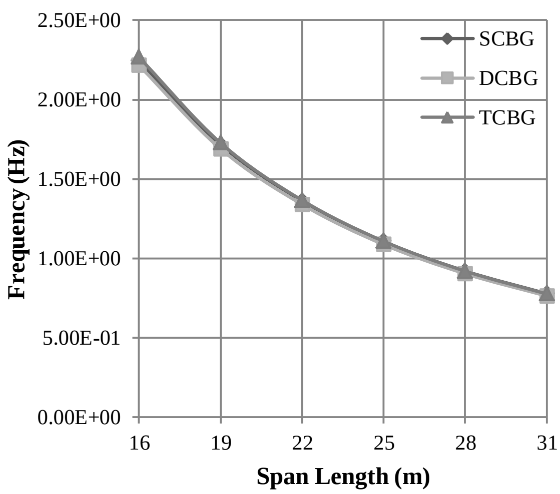


Figure 4.24: Variation of Frequency with Span Length of Box Girder

4.5.3 Span Length to Radius of Curvature Ratio

Two lanes with 120 m radius of curvature Single Cell Box Girder Bridge (SCBG), Double Cell Box Girder Bridge (DCBG) and Triple Cell Box Girder Bridge (TCBG) are analysed for different span length to the radius of curvature of ratio to illustrate the variation of longitudinal stresses at top and bottom, shear, torsion, moment, deflection and fundamental frequency with a span length of box girder bridges.

The variation of Longitudinal Stress at the top with span length to the radius of curvature of ratio of box girder bridges is shown in Figure 4.25. As the span length to the radius of curvature of ratio increases, longitudinal stress at the top of box girder increases for each type of Box Girder Bridge. Variation of longitudinal stress at the top of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 92 % for all the three cases and it shows that effect of span length to the radius of curvature of the ratio on longitudinal stress at the top is significant. Variation of longitudinal stress at top between three types of box girder is only about 1 %.

The variation of Longitudinal Stress at the bottom with a span length of box girder bridges is shown in Figure 4.26. As the span length to the radius of curvature of ratio increases, longitudinal stress at bottom of box girder increases for each type of Box Girder Bridge. Variation of longitudinal stress at the bottom of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 92 % for all the three cases and it shows that effect of span length to the radius of curvature of the ratio on longitudinal stress at the bottom is also significant. Variation of longitudinal stress at bottom between three types of box girder is about 4 %.

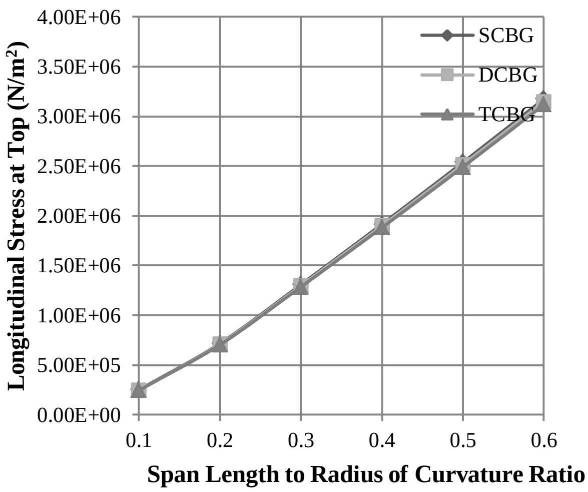


Figure 4.25: Variation of Longitudinal Stress at top with(L/R) Ratio of Box Girder

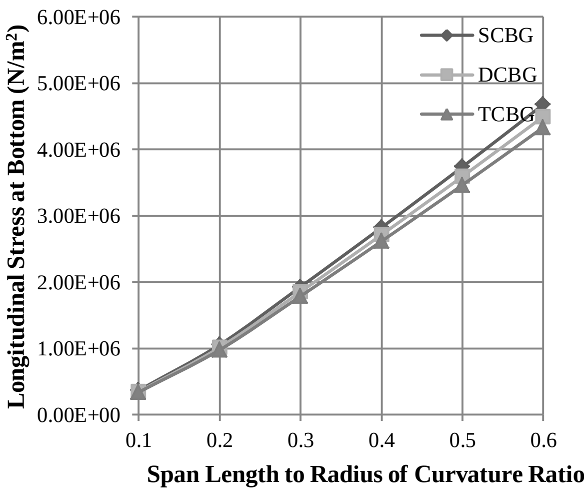


Figure 4.26: Variation of Longitudinal Stress at bottom with(L/R) Ratio of Box Girder

The variation of shear force with a span length of box girder bridges is shown in Figure 4.27. As the span length to the radius of curvature of ratio increases, Shear Force of box girder increases for each type of Box Girder Bridge. Variation of the shear force of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 47 % for all the three cases and it shows that effect of span length to the radius of curvature of the ratio on shear force is significant. Variation of shear force between three types of box girder is about 4 %.

The variation of torsion with span length of box girder bridges is shown in Figure 4.28. As the span length to radius of curvature of ratio increases, torsion of box girder increases for each type of Box Girder Bridge. Variation of torsion of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 80 % for all the three cases and it shows that effect of span length to the radius of curvature of ratio on torsion is significant. Variation of torsion between three types of box girder is only about 1 %.

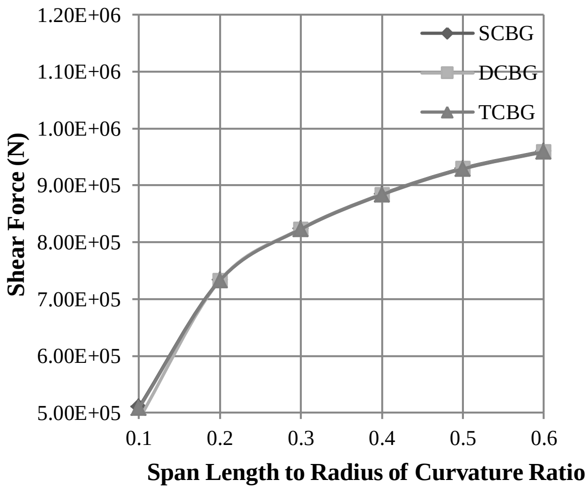


Figure 4.27: Variation of Shear Force with (L/R) Ratio of Box Girder

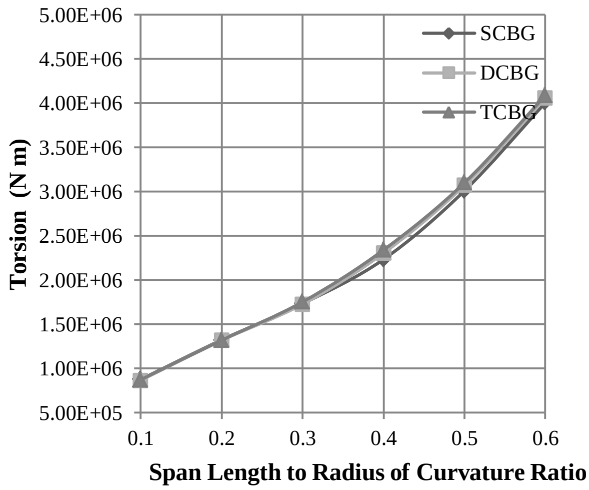


Figure 4.28: Variation of Torsion with (L/R) Ratio of Box Girder

The variation of moment with a span length of box girder bridges is shown in Figure 4.29. As the span length to the radius of curvature of ratio increases, moment of box girder increases for each type of Box Girder Bridge. Variation of moment of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 92 % for all the three cases and it shows that effect of span length to the radius of curvature of ratio on the moment is significant. Variation of moment between three types of box girder is only about 1.5 %.

The variation of deflection with a span length of box girder bridges is shown in Figure 4.30. As the span length to radius of curvature of ratio increases, deflection of box girder increases for each type of Box Girder Bridge. Variation of deflection of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 98 % for all the three cases and it shows that effect of span length to the radius of curvature of ratio on deflection is significant. Variation of deflection between three types of box girder is about 5-12 %.

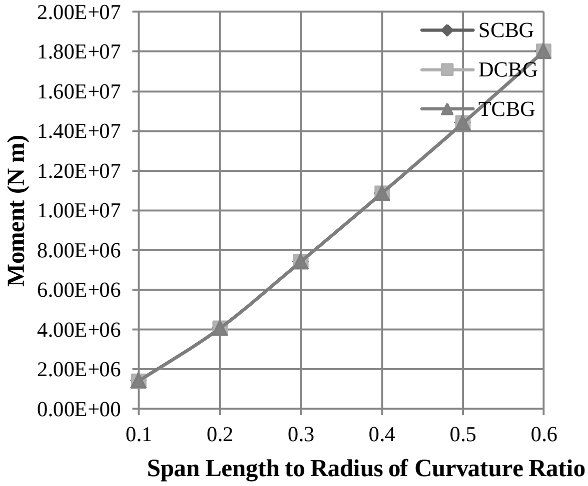


Figure 4.29: Variation of Moment with (L/R) Ratio of Box Girder

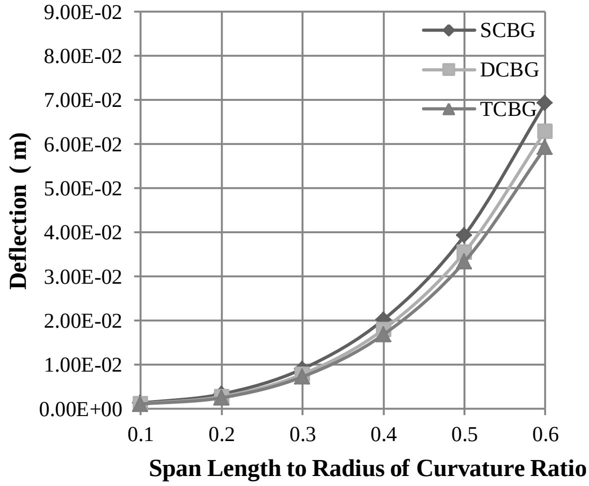


Figure 4.30: Variation of Deflection with (L/R) Ratio of Box Girder

The variation of frequency with a span length of box girder bridges is shown in Figure 4.31. As the span length to the radius of curvature of ratio increases, frequency of box girder decreases for each type of Box Girder Bridge. Variation of frequency of box girder between span length to the radius of curvature of ratio 0.1 – 0.6 is about 95 % for all the three cases and it shows that effect of span length to the radius of curvature of ratio on frequency is significant. Variation of frequency between three types of box girder is about 3 %.

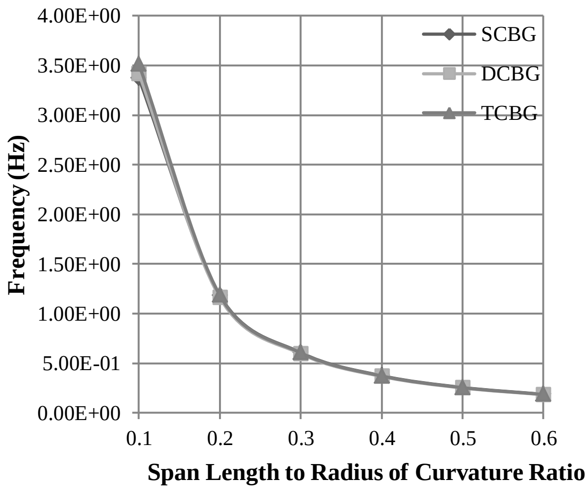


Figure 4.31: Variation of Frequency with (L/R) Ratio of Box Girder

4.6 SUMMARY

In this chapter, parametric study on behaviour of box girder bridges is carried out by using finite element method. The numerical analysis of finite element model is validated with model of Gupta et al. (2010). The parameter considered in this chapter to present the behaviour of SCBG, DCBG and TCBG bridges are radius of curvature, span length and span length to the radius of curvature ratio. Theses parameters are used to evaluate the response parameter of box girder bridges namely longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency of three types of box girder bridges. The results obtained from this parametric study are presented and discussed briefly in this chapter.

From the parametric study it is found out that as the radius of curvature increases, responses parameter longitudinal stresses at top and bottom, shear, torsion, moment and deflection are decreases for three types of box girder bridges and it shows not much variation for fundamental frequency of three types of box girder bridges due to the constant span length.

It is observed that as the span length increases, responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and fundamental frequency decreases for three types of box girder bridges.

It is noted that as the span length to the radius of curvature ratio increases responses parameter longitudinal stresses at top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and as span length to the radius of curvature ratio increases fundamental frequency decreases for three types of box girder bridges.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 SUMMARY

A metro system is an electric passenger railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. An elevated metro system is the most preferred form of metro structure due to ease of construction and less cost compared to other types of metro structures. An elevated metro system has two major components pier and box girder. In this project, study has been carried out on these two major elements.

In the first part of this study, the performance assessment on designed pier by Force Based Design and Direct Displacement Based Design is carried out. The design of the pier is done by both force based design method and direct displacement based design method.

In the second part, parametric study on behaviour of box girder bridges is carried out by using finite element method. The numerical analysis of finite element model is validated with model of Gupta et al. (2010). The parameter considered to present the behaviour of Single Cell Box Girder, Double Cell Box Girder and Triple Cell Box Girder bridges are radius of curvature, span length and span length to the radius of curvature ratio. These parameters are used to evaluate the response parameter of box girder bridges namely longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency of three types of box girder bridges.

5.2 CONCLUSIONS

The performance assessment of selected designed pier showed that,

- Force Based Design Method may not always guarantee the performance parameter required and in the present case the pier just achieved the target required.
- In case of Direct Displacement Based Design Method, selected pier achieved the behaviour factors more than targeted Values.

These conclusions can be considered only for the selected pier. For General conclusions large numbers of case studies are required and it is treated as a scope of future work.

The parametric study on behaviour of box girder bridges showed that,

- As the radius of curvature increases, responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are decreases for three types of box girder bridges and it shows not much variation for fundamental frequency of three types of box girder bridges due to the constant span length.
- As the span length increases, responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and fundamental frequency decreases for three types of box girder bridges.
- As the span length to the radius of curvature ratio increases responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and as span length to the radius of curvature ratio increases fundamental frequency decreases for three types of box girder bridges.

REFERENCES

1. Abdelfattah, F. A. (1997). Shear lag in steel box girders. *Alexandria Eng. J.*, Alexandria Univ., *Egypt*, 36 (1), 1110–1118.
2. Armstrong, W. L. and Landon, J. A. (1973). Dynamic testing of curved box beam bridge. Fed. Hwy. Res. and Devel. Rep. No. 73-1, *Federal Highway Administration*, Washington, D.C.
3. Balendra, T. and Shanmugam, N. E. (1985). Vibrational characteristics of multicellular structures. *J. Struct. Engrg.* , ASCE, 111 (7), 1449-1459.
4. Bazant, Z. P. , and El Nimeiri, M. (1974). Stiffness method for curved box girders at initial stress. *J. Struct. Div.*, 100 (10), 2071–2090.
5. Buchanan, J. D., Yoo, C. H., and Heins, C. P. (1974). Field study of a curved box-girder bridge. Civ. Engrg. Rep. No. 59, *University of Maryland*, College Park, Md.
6. Chang, S. T., and Zheng, F. Z. (1987). Negative shear lag in cantilever box girder with constant depth. *J. Struct. Eng.*, 113 (1), 20–35.
7. Chapman, J. C. , Dowling, P. J. , Lim, P. T. K. , and Billington, C. J. (1971). The structural behavior of steel and concrete box girder bridges. *Struct. Eng.*, 49 (3), 111–120.
8. Cheung, M. S., and Megnounif, A. (1991). Parametric study of design variations on the vibration modes of box-girder bridges. *Can. J. Civ. Engrg*., Ottawa, 18(5), 789-798.
9. Cheung, M. S., and Mirza, M. S. (1986). A study of the response of composite concrete deck-steel box-girder bridges. *Proc., 3rd Int. Conf. on Computational and Experimental Measurements*, Pergamon, Oxford, 549-565.
10. Cheung, M. S., Chan, M. Y. T., and Beauchamp, T. C. (1982). Impact factors for composite steel box-girder bridges. *Proc., Int. Assn. for Bridges and Struct. Engrg*. IABSE Colloquium, Zurich, 841-848.

11. Cheung, Y. K. , and Cheung, M. S. (1972). Free vibration of curved and straight beam-slab or box-girder bridges. *IABSE Periodica*, Zurich, 32(2), 41-52.

12. Cheung, Y. K., and Li, W. Y. (1991). Free vibration analysis of longitudinal arbitrary curved box-girder structures by spline finite-strip method. *Proc., Asian Pacific Conf. on Computational Mech.,* Pergamon, Oxford, 1139-1144.

13. Chu, K. J. , and Jones, M. (1976). Theory of dynamic analysis of box-girder bridges. *Int. Assn. of Bridge and Struct. Engrg.*, Zurich, 36(2), 121-145.

14. Chu, K. J., and Pinjarkar, S. G. (1971). Analysis of horizontally curved box girder bridges." *J. Struct. Div.* , 97 (10), 2481–2501.

15. Daniels, J. H., Abraham, D., and Yen, B. T. (1979). Fatigue of curved steel bridge elements—effect of internal diaphragms on fatigue strength of curved box girders. *Rep. No. FHWA-RD-79-136*, Federal Highway Adminstration, Washington, D.C.

16. Design Basis Report of Bangalore Metro Phase I (2003). *Bangalore Metro Rail Corporation Limited*. Bangalore.

17. Detailed Project Report of Bangalore Metro Phase I (2003). *Bangalore Metro Rail Corporation Limited*. Bangalore.

18. Dezi, L. (1985). Aspects of the deformation of the cross-section in curved single-cell box beams. *Industria Italiana Del Cemento,* 55(7–8), 500–808

19. Dilger, W. H., Ghoneim, G. A., and Tadros, G. S. (1988). Diaphragms in skew box girder bridges. *Can. J. Civ. Eng* , 15 (5), 869–878.9ku

20. Fafitis, A., and Rong, A. Y. (1995). Analysis of thin-walled box girders by parallel processing. *Thin-Walled Struct.*, 21(3), 233–240.

21. Fam, A. R. M. (1973). Static and free-vibration analysis of curved box bridges. Struct. Dyn. Ser. No. 73-2, Dept. of Civ. Engrg. and Appl. Mech., *McGill University*, Montreal.

22. Fam, A. R., and Turkstra, C. J., (1975). A finite element scheme for box bridge analysis. *Comput. Struct. J.*, 5, 179–186.
23. FEMA 273 (1997). NEHRP Guidelines for the seismic rehabilitation of buildings. *Federal Emergency Management Agency*, Applied Technology Council, Washington D.C., USA.
24. FEMA 356 (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. *American Society of Civil Engineers*. USA.
25. Galdos, N. H. (1988). A theoretical investigation of the dynamic behaviour of horizontally curved steel box-girder bridges under truck loadings. PhD thesis, *University of Maryland at College Park*.
26. Galdos, N. H., Schelling, D. R., and Sahin, M. A. (1993). Methodology for impact factor of horizontally curved box bridges. *J. Struct. Engrg.* , ASCE, 119 (6), 1917-1934.
27. Galuta, E. M., and Cheung, M. S. (1995). Combined boundary element and finite element analysis of composite box girder bridges. *Comput. Struct. J.*, 57 (3), 427–437.
28. Gupta P.K, Singh KK, Mishra A. (2010). Parametric Study on Behaviour of Box-Girder Bridges using Finite Element Method. *Asian Journal of Civil Engineering (Building and Housing)*, *11*(1), 135–148.
29. Heins, C. P. , and Sahin, M. A. (1979). Natural frequency of curved box-girder bridges. *J. Struct. Div.*, ASCE, 105 (12), 2591-2600.
30. Heins, C. P., and Lee, W. H. (1981). Curved box-girder bridge test: Field test. *J. Struct. Div.*. ASCE. 107 (2), 317-327.
31. Huang, D., Wang, T., and Shahaway, M. (1995). Vibration of thin-walled box-girder bridges exited by vehicles. *J. Struct. Engrg.* , ASCE, 121 (9), 1330-1337.
32. Huang, D., Wang, T., and Shahaway, M. (1998). Vibration of horizontally curved box-girder bridges due to vehicles.*Comp. and Struct.*, 68(5), 513-528.
33. IBC (2003). International building code. *International Code Council. Inc*. Virginia. USA.

34. Inbanathan, M. J., and Wieland, M. (1987). Bridge vibration due to vehicle moving over rough surface. *J. Struct. Engrg.* , ASCE, 113 (9), 1994-2008.

35. IRS Concrete Bridge Code (1997). Code of Practice for Plain, Reinforced & Prestressed Concrete for General Bridge Construction Code. *Research Designs and Standards Organisation*, Lucknow.

36. IS 13920 (1993). Indian Standard Code of Practice for Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces. *Bureau of Indian Standards*, New Delhi.

37. IS 1893 Part 1 (2002). Indian Standard Criteria for Earthquake Resistant Design of Structures. *Bureau of Indian Standards*. New Delhi.

38. IS 456 (2000). Indian Standard for Plain and Reinforced Concrete - Code of Practice. *Bureau of Indian Standards*. New Delhi.

39. Ishac, I. I., and Smith, T. R. G. (1985). Approximations for moments in box girders. *J. Struct. Eng.* , 111 (11), 2,333–2,342.

40. Jeon, S. M., Cho, M. H., and Lee, I. (1995). Static and dynamic analysis of composite box beams using large deflection theory. *Comput. Struct.* , 57 (4), 635–642.

41. Jirousek, J., and Bouberguig, A. (1979). A macro-element analysis of prestressed curved box-girder bridges. *Comput. Struct.*, 10 , 467–482.

42. Kashif, A. M. (1992). Dynamic response of highway bridges to moving vehicles. PhD dissertation, Dept. of Civ. Engrg., *Carleton University*, Ottawa.

43. Komatsu, S. , Nakai, H. , and Nakanishi, M. (1971). Statistical analysis of horizontally curved skew box girder bridges. *Trans., Jpn. Soc. Civ. Eng.*, 3 (2), 134–135.

44. Kou, C., Benzely, S. E., Huang, J., and Firmage, D. A. (1992). Free vibration analysis of curved thin-walled girder bridges. *J. Struct. Engrg.*, ASCE, 118 (10), 2890-2910.

45. Kurian, B. (2005). *Estimation of Transverse Bending Moments and Collapse Loads of Single-Cell Concrete Box-Girder Bridge.* Ph.D Thesis. *Indian Institute of Technology Madras*, India.

46. Kurian, B. and Menon, D. (2007). Estimation of Collapse Load of Single-Cell Concrete Box-Girder Bridges. *J. Bridge Eng.*, 12(4), 518–526.

47. Lim, P. T., Kilford, J. T., and Moffatt, K. R. (1971). Finite element analysis of curved box girder bridges. *Devel Bridge Design and Construction,* U.K., 264–286.

48. M.J.N. Priestley, G. M. Calvi and M. J. Kowalsky. (2007). Displacement Based Seismic Design of Stuctures. *Iuss Press*, Pavia, Italy.

49. Malcolm, D. J., and Redwood, R. G. (1970). Shear lag in stiffened box girders. *J. Struct. Div.*, 96 (7), 1403–1419.

50. Mirza, M. S. , Manatakos, C. K. , Murali, R. D. , Igwemezie, J. O. , and Wyzykowski, J. (1985). An analytical-experimental study of the behavior of a composite concrete deck-steel box-girder bridge. Rep., Public Works Canada, Dept. of Civ. Engrg. and Appl. Mech., *McGill University*, Montreal.

51. Mirza, M. S., Ferdjani, A., Hadj-arab, A., Joucdar, K., and Khaled, A. (1990). An experimental study of static and dynamic responses of prestressed concrete box girder bridges." *Can. J. Civ. Eng.*, 17 (3), 481–493

52. Mishra, P. K., Das, S., and Dey, S. S. (1992). Discrete energy method for the analysis of right box-girder bridges. *Comput. Struct.* , 43 (2), 223–235.

53. Moffatt, K. R., and Dowling, P. J.(1975). Shear lag in steel box girder bridges. *Struct. Eng.*, 53 (10), 439–448.

54. Moffatt, K. R., and Lim, P. T. K. (1976). Finite element analysis of composite box girder bridges having complete or incomplete interaction. *Proc., Inst. Civ. Eng., Part 2*, 63 (3), 1–22.

55. Rabizadeh, R. O., and Shore, S. (1975). Dynamic analysis of curved box-girder bridges. *J. Struct. Div.*, ASCE, 101 (9), 1899-1912.

56. Ramesh, C. K., Kalani, M., and Bhandari, V. S. (1976). Analysis of single-cell box-section for a curved bridge deck. *J. Ind. Roads Congr.* , 37 (1), 85–104.

57. Samaan, M., Kennedy, J. B.,Sennah, K. Dynamic Analysis of Curved Continuous Multiple-Box Girder Bridges. *Journal of Bridge Engineering*, *12*(2), 184–193.

58. SAP 2000 NL (2000). *Computers and Structures. Inc*. University Avenue. Suite 540. Berkeley. California. USA.

59. Sargious, M. A., Dilger, W. H., and Hawk, H. (1979). Box girder bridge diaphragms with openings. *J. Struct. Div.*, 105 (1), 53–65.

60. Schelling, D. R., Galdos, N. H., and Sahin, M. A. (1992). Evaluation of impact factors for horizontally curved steel box bridges. *J. Struct. Engrg.*, ASCE, 118 (11), 3203-3221.

61. SeismoSoft (2013) SeismoStruct Version 6 - A computer program for static and dynamic nonlinear analysis of framed structures [online]. < http://www.seismosoft.com/ >

62. Sennah, K. and Kennedy, J. (2001).State-of-the-Art in Design of Curved Box-Girder Bridges. *J. Bridge Eng.*, 6(3), 159–167

63. Sennah, K. and Kennedy, J. (2002). Literature Review in Analysis of Box-Girder Bridges.*J. Bridge Eng.*, 7(2), 134–143.

64. Sennah, K. M., and Kennedy, J. B. (1997). Dynamic characteristics of simply supported curved composite multicell bridges. *Can. J. Civ. Engrg.*, Ottawa, 24, 621- 636.

65. Sennah, K. M., and Kennedy, J. B. (1998). Vibration of curved continuous composite multicell bridges. *Can. J. Civ. Engrg.*, Ottawa, 25, 139-150.

66. Senthilvasan, J., Brameld, G. H., and Thambiratnam, D. P. (1997). Bridge-vehicle interaction in curved box-girder bridges. *Microcomputers in Civ. Engrg.*, Oxford, 12(3), 171-181.

67. Shanmugam, N. E. , and Balendra, T. (1986). Free vibration of thin-walled multicell structures. *Thin-Walled Struct.*, 4(6), 467-485.

68. Shushkewich, K. W. (1988). Approximate analysis of concrete box girder bridge. *J. Struct. Eng.*, 114 (7), 1644–1657.

69. Sisodiya, R. G., Cheung, Y. K., and Ghali, A. (1970). Finite-element analysis of skew, curved box girder bridges. *Int. Assoc. Bridges Struct. Eng.*, (*IABSE*), 30 (II), 191–199.

70. STAAD.Pro V8i (2008). *Bentley Systems*, *Inc*. Research Engineers, International Headquarters, CA, USA.

71. Tabba, M. M. (1972). Free-vibration of curved box-girder bridges. MEng thesis, Dept. of Civ. Engrg. and Appl. Mech., *McGill University*, Montreal.

72. Templeman, A. B., and Winterbottom, S. K. (1979). Optimum design of concrete cellular spine beam bridge decks. *Proc., Inst. Civ. Eng., London*, 67(2), 389–409.

73. Turkstra, C. J. , and Fam, A. R. M. (1978). Behavior study of curved box bridges. *J. Struct. Div.*, ASCE, 104 (3), 453-462.

74. Wang, T., Huang, D., and Shahawy, M. (1996). Dynamic behavior of continuous and cantilever thin-walled box-girder bridges. *J. Bridge Engrg.* , ASCE, 1 (2), 67-75.

75. William, K. J., and Scordelis, A. C. (1972). Cellular structures of arbitrary plan geometry. *J. Struct. Div.*, 98 (7), 1377–1394.